DEVELOPING THE ALL ELECTRIC MARINE GAS TURBINE

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ABSTRACT

Following the design shift in Naval ship architecture from conventional mechanical through hybrid to Integrated Electric Propulsion (IEP), the starting philosophy of prime movers needs to be rationalised so as to interact and augment the new propulsion configurations and electrical distribution whilst remaining cost effective. To fulfil this initial requirement the UK Ministry of Defence contracted Ultra Electronics to work in partnership to develop and demonstrate a gas turbine Electric Start & Generation System (ESGS) (produce electricity via the start motor). The programme is to demonstrate full control over the gas turbine starting system and associated maintenance features together with generating sufficient electrical power that can be used to supply all the gas turbine alternator auxiliaries. Stemming from this development work the potential was realised for electrifying the on-engine auxiliaries and combining these requirements with the start and generation system whilst removing the auxiliary gearbox thus creating an electric engine capable of self-sustainability.

This paper will give an overview of the requirements placed on the starting system of a gas turbine that can be employed for a ship utilising an electric architecture. It will include the capability enhancements that an electrical starting system can offer and will discuss the design and capabilities of the ESGS. It will also discuss factory acceptance testing and on-engine trials. The paper will then outline the next logical step in the process, the All Electric Engine. Conclusions will be drawn from the initial test results and comparisons between the design of existing mechanical gas turbine start systems, the ESGS and the proposed all electric engine system.

Introduction

This paper describes the development path to an all-Electric Gas Turbine (GT) Engine System with the electrical actuation of all auxiliary functions. Steps towards this objective include the development of Electric Start Systems (employing electric drive via an accessory gear box) and Electric Start and Generation Systems (ESGS) (allowing the production of electricity via the start motor). Any of these systems can be integrated with an energy storage system to provide a 'black start' (starting an engine in the absence of all platform electrical supplies) capability. However 'black start' is not an essential feature of any of these systems and will not be discussed in any detail in this paper.

In 2001 the Royal Navy (RN) in conjunction with BAE Systems made the decision to implement a hydraulic system in place of High Pressure (HP) (reduced) air for the Gas Turbine (GT) starting mechanism in the Type 45 Daring Class Destroyer (T45). The prime reason for this change was the belief that moving away from a Ship's HP air system could make significant Whole Life Cost (WLC) savings. Eighty per cent of the ship's HP air system capacity is designed to accommodate GT start. The scope of the hydraulic system was to provide start and motoring functions for the GT. At that time all parties, following an independent review of GT starting methods, believed that an electric start system for an aero derivative GT was not feasible, as there were no suitable power-dense electric motors available. Therefore a hydraulic start system was adopted.

Recent advances in power dense electric motor and drive technology mean that electric start of GTs is now possible. Also the system and operational changes associated with the move to an electrical propulsion architecture mean that there are additional benefits to be gained. In particular is the potential for an ESGS to regenerate allowing for reversionary mode operation of GTs independent of the ships Low Voltage (LV) supplies. This in turn opens up the possibility of electrifying the auxiliary drives and thus dispensing with the GT auxiliary gearbox whilst maintaining the self-sustainability of the engine. In realising these benefits the UK MoD awarded a contract to Ultra Electronics in 2003 for the development of a GT ESGS demonstrator.

The ESGS demonstrator was designed and built using advanced materials to produce a very compact, high torque motor capable of starting and generation, and Pulse Width Modulation (PWM) technology to create a suitable controller. In 2005, following Factory Acceptance Tests (FATs) the demonstrator was trialled on a Rolls-Royce MT30 at Filton, UK. The starting requirements and auxiliary loads of the engine used for this test are significantly higher than other GTs such as the WR-21, LM2500 and LM6000 so the results are not limited or engine specific.

BACKGROUND

Existing GT start configurations

Current architectures utilised by the RN for their major warships are predominantly mechanical and rely heavily upon pressurised mediums such as air and hydraulic fluids. HP air provides a number of functions essential for the propulsive power of the ship that includes:

- GT start and motoring facilities via reduced HP air.

- Storage capacity in pressurised cylinders allowing for 'black start' of GTs.
- The facility to power air driven fuel pumps to operate in isolation of LV power. On later ships this has been changed to a fuel accumulator system allowing for a finite provision of fuel to the GT.
- The facility to power air driven Forced Lubrication (FL) pumps for main gearboxes to allow for operation in isolation of LV power.

HP air provides compact stored energy, unfortunately when installed as a 'ring main' system throughout the ship, the Unit Production Cost (UPC) of the components and the installation costs are high. Additionally the Through Life Costs (TLC), primarily due to maintenance requirements, are considerable giving the system a high Whole Life Cost (WLC).

All Electric Ship

With the transition from mechanical to electrical systems and the introduction of the All Electric Ship the requirements from the power generated are now different and the operating philosophy is changing with it. Of significant note is the reduction in the number of prime movers. The introduction of the power station concept means that there are no longer engines dedicated purely to propulsion or electrical generation. Power is only produced in an electrical form at a given voltage via Gas Turbine Alternators (GTAs) or Diesel Generators (DGs). This high voltage (HV) power is then used dependent on the ship's requirement for propulsion, weapons or auxiliaries and is converted or stepped down to LV where required. The prime movers selected for the ship are matched to the operating profile for maximum speed, endurance and harbour/low load requirements. With this electrical architecture it is possible to utilise single generator operation thereby reducing operating costs. This cost reduction is achieved by reduced fuel consumption, lower maintenance costs and extending the installed life of the prime movers by reducing the total number of hours run. This is achieved by minimising the number of generators in operation at any one time.

With this reduction in the number of prime movers, availability of them becomes paramount. Of increased importance is the availability of LV power, which is only generated when a prime mover is running. For high power GTAs the associated auxiliary systems for starting, providing enclosure ventilation, fuel supply, alternator lubrication oil supplies together with engine control and protection are powered from the high priority LV distribution system. Unless batteries or a form of Uninterruptible Power Supply (UPS) are fitted to the essential systems for these prime movers then it will not be possible to either start them or run them in isolation of LV power. An ESGS could operate in a regenerative mode, which when coupled to suitable energy storage, output conditioning and distribution would enable localised black start and autonomous continuous operation. This feature has the potential to enhance the war fighting capability of an electric ship by allowing the high power GTA to continue to provide power to the HV distribution system regardless of the local condition of the LV distribution system that normally provides power to the GTA auxiliaries.

Changes to Auxiliary Design Philosophy

As mentioned above the T45 will not utilise an air start system for its GTs and will instead use a hydraulic starter. These systems are evolutionary, as they are presently in-service with several Navies. The primary benefit that hydraulic systems offer over HP air is cost. In considering the UPC of a HP air system to be fitted to a typical Destroyer 85% of the material cost is attributable to the major components, these being compressors (with driers), air reservoirs and reducing stations. If this were replaced with a hydraulic start and localised air systems (required for breathing air, diving air and other ships' services) the cost would be substantially reduced. The implications of adopting localised units compared to ring main systems also decreases the installation costs. Additionally pressurised air systems incur substantial repair bills during ship upkeep periods. Studies have shown that adopting a hydraulic GT start system in place of a pneumatic one can make considerable savings, both in terms of UPC and TLC. For an ESGS to be successful it must be able to compete with these basic costs, especially if it is to be inserted technology.

However, it is not cost alone that has brought about a change to the starting mechanism for GTs. Linked to cost are the changes that have taken place in the basic auxiliary design philosophy. New ship designs are increasingly influenced by the benefits of the all electric generation and distribution arrangement for propulsion and auxiliary systems.[Ref.1] This includes the fundamental shift in design from large HP air or hydraulic ring main systems, offering simplicity of stored energy and redundancy through reconfiguration by cross-connection, to localised units. The emphasis in this change is to reap the benefits gained from electric actuation and remove high maintenance systems. Additionally the pressurised HP air or hydraulic ring main, together with storage cylinders, is particularly vulnerable to battle damage through shock and when containing HP air or particular hydraulic fluids present a considerable risk of fire or explosion.

Removal of HP air systems does however result in the loss of ride-through capability (ability of the GT to continue operating in the absence of platform LV supplies) of auxiliary systems essential to GT operation.

REQUIREMENTS AND INCREASED CAPABILITY OF A GT ESGS

For an ESGS to be considered a viable option for selection it must, as a minimum be capable of performing the basic platform requirements as detailed earlier. Additionally to be successful the technology must be capable of insertion into existing platforms, be compatible with those systems and deliver the benefits of a lower WLC. Therefore an ESGS needs to fulfil the following requirements:

- Start, purge and wash of the engine
- Black start capable
- Self-sustainable in isolation of LV supplies by providing all auxiliary power requirements for the GT including fuel, engine lubrication, alternator bearing lubrication, control and enclosure ventilation.

- Safe shutdown of the engine
- Insertable technology
- Equivalent or lower UPC to hydraulic starters
- Possess a lower WLC than existing start systems
- Provide ease of control

In addition to these enhanced capabilities the ESGS will be able to provide an increased war fighting effectiveness for ships by facilitating an 'island generation' capability. This is supported by availability studies due to the increased level of redundancy now incorporated within the propulsion design. These features all assist in maintaining power to command.

ESGS DESIGN

Figure 1 illustrates a block diagram for a typical ESGS. The ships LV system is converted to a DC bus, local to the gas turbine, via a static converter. This DC bus acts as a power distribution system from the starter-generator to the engine auxiliaries. It may also be connected to an energy storage system. A variable speed drive inverter interfaces the DC bus with the starter-generator.

The ESGS is powered by either the ship's LV supplies or its energy storage medium on start-up. The start motor will then act in the conventional way of engaging with the gearbox of the GT thereby indirectly spinning the compressor and turbines via the shafting arrangement. The starter will continue to provide torque assistance until the gas generator becomes self-sustaining. When the engine has reached this speed the starter motor acts as a generator and can provide power to the auxiliaries and the energy storage device if required.

The two basic constituent parts for the ESGS are the starter generator and the associated power electronics. The ESGS has been designed for the option of integration with an energy storage device, which is subject to its own development programmes.

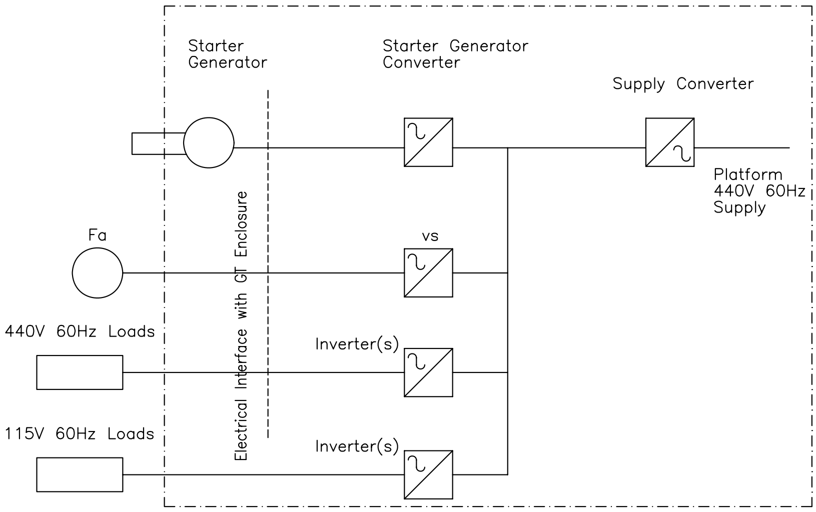

Fig. 1 Electric Start & Generation System

Starter generator technology selected for the ESGS

The biggest challenge in the development of the ESGS was seen to be the development of a sufficiently power dense motor. This challenge has now been overcome. Four machine technology options were considered for the starter generator, which were:

- Induction
- Synchronous wound rotor
- Synchronous permanent magnet
- Switch reluctance

When utilised in an ESGS the prime design criteria for these machines, whose merits have been discussed previously [Ref.2], are weight, size, control and cost. An induction machine has been selected as it offers the best compromise between risk, safety, performance, size and weight. Although the basic machine technology was widely available, considerable design effort to enhance its performance has been undertaken. This design has now progressed to the stage that the motor has been designed, built and trialled on an engine.

Power electronics

Power Electronics was the other predominant area of work involved in this programme and was particularly complex to incorporate all of the functions that were demanded of it. The basic functional blocks that comprise an ESGS capable of self-sustaining a GT have been illustrated at Figure 1. As mentioned above, an induction machine has been selected for the starter generator, which is mounted to the engine's accessory gearbox and is connected by electrical cables to the off-engine hardware. The off-engine hardware comprises a number of items located in a convenient position outside the engine enclosure. These items are:

A starter-generator converter. This is a variable-speed drive inverter, which controls the speed and torque of the induction machine when it is driving the engine. It controls the electrical power flow from the induction machine when it is being driven as a generator by the engine.

A supply converter. This converts the platform 440V 60Hz supply to a DC supply suitable as an input to the starter-generator converter. When the platform 440V supply is available, this is used to provide the power required to start the engine.

A number of inverters to provide power to AC loads from the DC supply. These AC loads are necessary for operation of the gas turbine. When the gas turbine is running, the loads are supplied with power from the starter-generator. This allows the gas turbine to be self-sustaining. This power supply could be considered as the normal supply for the auxiliary with its alternative being supplied from the ship's LV system via an Automatic Change-Over Switch (ACOS).

MT30 TESTS

The Electric Start Machine was fitted to the accessory gearbox of a Rolls-Royce MT30 gas turbine, in the purpose-designed MT30 test bed [Ref.3]. The off-engine cubicles were installed within the test facility, outside the engine enclosure. The Modbus TCP (industry standard interface) signals from the FADEC (Full Authority Digital Engine Control), which would otherwise interface with the hydraulic start system, were connected into the ESGS controller unit to perform identical functions.

The ESGS was initially used to carry out a series of dry cranks at various controlled speeds in order to characterise the resistance torque curve of the MT30 HP shaft. It was then used to start the engine. Having proven its ability to do so reliably, the ESGS was used to carry out a series of starts. The ESGS performed flawlessly, carrying out over 70 successful starts.

The ESGS was then used to demonstrate regeneration of electrical power from the MT30 over the full speed and power range. Power was absorbed by a resistive load bank. A series of tests were carried out to demonstrate the capability to regenerate a useful level of power continuously and to characterise the effects on the engine of significant load switching transients.

Figure 2 shows a typical start sequence. The ESGS holds the HP (High Pressure) shaft at the pre-programmed cranking speed until light-off is complete. It then provides torque assistance in accordance with a pre-programmed profile. When engine self sustaining speed has been exceeded, the ESGS enters generation mode.

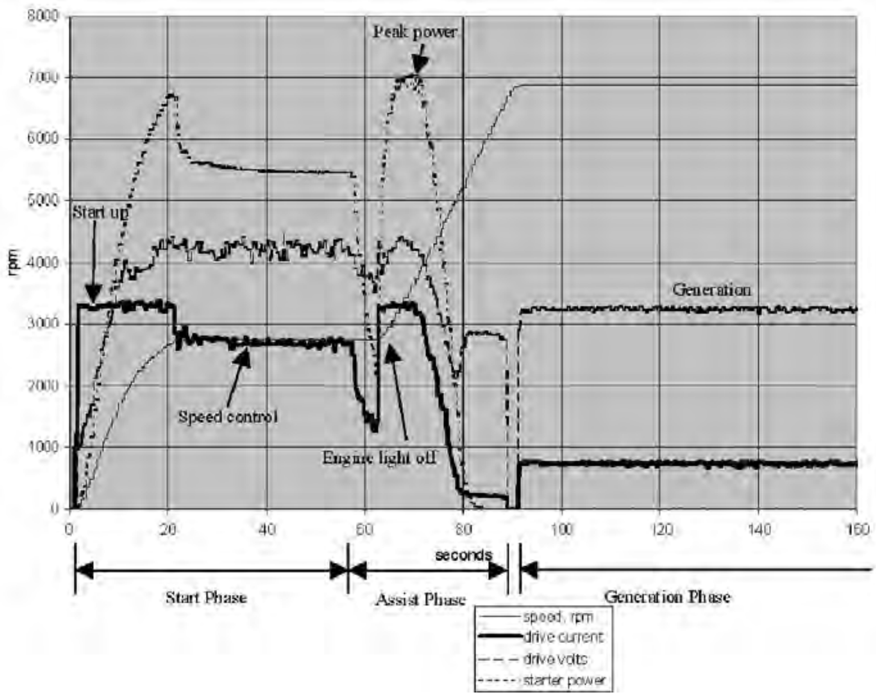

Fig. 2 Typical MT30 Start using ESGS

The starting torque, light-off speed and assistance torque requirements of the MT30 are all significantly greater than those of the LM2500, for which the machine was specified. The tests show that the induction machine, built to a novel design and using advanced materials, outperformed its specified requirement. The machine proved to be capable of reliably, accurately and repeatedly starting the MT30.

The control of torque and starter speed has been demonstrated to be more precise than that achieved by an existing hydraulic start system.

Optimisation of the ESGS performance over a wide speed range, from normal cranking speeds up to GT overspeed, presented a significant challenge that has been overcome. The induction machine is inherently capable of producing rated motoring torque up to higher speeds than normally used to crank the LM2500.

ALL ELECTRIC ENGINE DEVELOPMENT

The next logical step following the successful demonstration of an ESGS, described above, is the development of an All Electric Engine. The Electric Engine concept considers the replacement of mechanical GT auxiliary drives from the auxiliary gearbox with electric drives powered by LV supplies or, in emergency, the ESGS. This offers a number of possible benefits:

Removal of the auxiliary gearbox, thereby dispensing with a large mass hung under the centre of the engine. This removes one of the major constraints from a shock perspective.

Freedom to locate auxiliary drives such as the fuel pump in any convenient location, such as outside the module, improving access and maintainability, thereby offering increased engine availability.

Variable speed auxiliary drives, providing better control and the potential to save energy by matching delivery to requirement.

Reduced Whole Life Cost

In order to realise these benefits and produce a navalised solution a number of challenges will need to be overcome, including whether any changes to engine control and operation are required and the need to reconfigure engine accessory layout and associated dressings.

Conclusions

This paper has compared the various gas turbine starting technologies:

- The traditional starting technology of a HP air system offers a proven black start capability independent of mains LV electrical supplies with only 24V battery control required. However the system required is extensive, requires a lot of maintenance and hence is costly. Also it is susceptible to action damage.
- The hydraulic alternative is powerful and is less extensive than HP systems, but it is still high maintenance and does not have the bulk storage capacity of air systems. The pressurised hydraulic fluid also presents a fire risk and a handling hazard.
- Electric start and generate is a self contained, low maintenance system with the ability to supply power to off engine auxiliaries, and possibly other equipments, providing independence from LV supplies, thereby reducing the vulnerability of electric propulsion systems. It also offers unparalleled control of gas turbine starting and is well suited to the all-electric ship philosophy. It is capable of integration with an energy storage system that links into the electrical architecture, to offer black start of GTs.
- Further benefits can be gained by adoption of the all electric engine, building on the benefits of the electric start and generate system.

- This will increase the availability of the engine by allowing greater flexibility in the positioning and redundancy of gas turbine auxiliaries. In doing so it removes the auxiliary gearbox, reducing susceptibility to shock. Other benefits include reduction in energy use and reduced cost.

The successful test of the ESGS, starting a large marine GT and generating a useful level of electrical power from it, is a major milestone in the overall development of the Electric Engine System. It offers the ship Prime Contractors a technology that has many benefits at a low cost and risk, and is supported by the Royal Navy and US Navy alike.

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